NON-INVASIVE TECHNOLOGIES FOR INTRACRANIAL PRESSURE/VOLUME MEASUREMENT

A. Ragauskas, V. Petkus
Telematics Scientific Laboratory, Kaunas University of Technology, Lithuania

Abstract – **The paper shows that innovative technologies for non-invasive monitoring of the cerebral blood flow autoregulation, cerebral blood flow pulse and slow waves also for the registration of the reactions to the neurodiagnostic tests can be developed on the basis of the precise measurement of brain parenchyma acoustic characteristics. The innovative technological equipment for such measurement has been developed. The clinical studies proving the validity of the concepts chosen have been carried out. For the first time the innovative non-invasive method has been designed for the ICP absolute value measurement without the necessity of individual calibration of system "non-invasive meter – patient".**
Keywords **- Intracranial pressure, non-invasive monitoring, time-of-flight method, transcranial Doppler.**

I. INTRODUCTION

Head injury has devastating economic and social consequences both to the victim and to the society that supports the victim. The World Health Organization estimate that by the year 2010, one in ten families will have a family member with a head injury. Since head injury is more prevalent in the young and the associated disability does not significantly reduce life expectancy, the result is that the social and economic costs incurred by health and welfare organizations are long term and substantial [1].

Direct measurement of intracranial pressure (ICP) remains the mainstay of detecting brain swelling after the head injury before pressure rises to levels damaging the brain function. At present, the measurement techniques are invasive and require either the placement of a catheter-tip strain gauge device into the brain tissue directly or a fluid filled catheter placed into the cerebral spinal fluid space within the brain. However, the implementation of such procedures is related to entailing the risk of causing intracerebral bleeding, risk of infection inside the brain or other undesirable phenomena that can deteriorate the outcome. To avoid these problems, the non-invasive ICP monitoring technology is needed.

The ideas of the measurement of ICP non-invasively have been appearing since 1980. There are many patents [2,3,6-16], the authors of which attempt to find the objects or physiological characteristics of cerebrospinal system that would be related to the ICP and monitor them non-invasively. Most of the proposed monitoring technologies are based on the ultrasound application and are capable of monitoring physiological properties such as blood flow in intracranial or intraocular vessels, pulsations of the cerebral ventricles, cranium diameter or acoustic properties of the cranium. However, there are a few main questions encountered by a lot of authors of these works:

1) Which biophysical parameter of a cerebrospinal system is a stable and repeatable function of ICP or cerebral perfusion pressure (CPP) only?

2) Is that function linear and more or less independent on such main influential factor as arterial blood pressure (ABP) and how it depends on the cerebral blood flow autoregulation?

3) How to calibrate non-invasively the system "individual patient – non-invasive ICP or CPP meter"?

Unfortunately the answers to these questions based on reliable clinical studies still have not been found.

Recently, a new method [2] for non-invasive measurement of intracranial volume or pressure has been created in Telematics Scientific Laboratory of Kaunas University of Technology (Lithuania) which uniquely purports to measure the intracranial pulsation of small intracranial blood vessels. This method may be of more clinical value as the microvasculature is the major source of cerebrovascular resistance which determines the intracranial cerebral blood flow and it is responsible for cerebral blood flow autoregulation. Another innovative method [3] includes a means based on the transcranial Doppler multi-depth technique for a non-invasive absolute ICP value measurement without the individual calibration problem.

The main applications of these devices are the following:

- fast non-invasive diagnosing of brain injury during the first "golden hour" after the casualty case,
- non-invasive brain or spinal cord injury physiological monitoring during the intensive care,
- non-invasive diagnosing of brain physiological status during the rehabilitation period,
- diagnosing and monitoring of the reactions of cerebral blood flow autoregulation system and parenchymal blood volume/ICP on different pharmacological influences or physical loads (space medicine, sport medicine, etc.).

Both innovative methods are described in this paper and clinical results are also presented.

II. METHODOLOGY

The background of the non-invasive intracranial volume or pressure measurement methodology is the relationships between the ultrasound speed in the cerebral parenchymal acoustic path and blood volume inside the cerebral parenchyma (CBV), cerebrovascular resistance (CVR) and also CPP, ABP and ICP. These relationships could be explained by the changes of the diameter of cerebral arterioles as a result of cerebral blood flow autoregulation (Fig. 1). In the case of normal autoregulation (Fig. 1b) the diameter of cerebral arterioles decreases (Fig. 1a) when CPP increases within the linear range of CVR/CPP dependence (Fig. 1c). The blood volume also changes inside the cerebral parenchymal acoustic path (Fig. 1d) as a result of the autoregulatory change of cerebral arterioles diameter. It was

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Abstract

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shown in our theoretical studies [4,5] that the relationship between ultrasound speed inside the transintracranial parenchymal acoustic path and the blood volume inside cerebral parenchyma is linear.

In the case of normal cerebral autoregulation and stabilized ABP, the axis of CPP could be presented as the axis of ICP with the opposite direction (Fig. 1e). In Fig. 1e this situation is presented as an ideal case when ABP=140 mmHg and ABP is stable. In this case the relative change of ultrasound speed increases linearly with the increment of ICP. In a more general case Fig. 1e when CPP is changing as a result of ABP and ICP changes, the relative change of ultrasound speed decreases linearly with the increment of CPP.

Ultrasonic time-of-flight method for non-invasive cerebral blood volume/ICP/CPP pulse waves, respiratory waves, slow waves and trends monitoring. The concept of this method is as follows [2]:

- the intraventricular or supraventricular parenchymal acoustic path which crosses the human head is used (Fig. 2a). The parenchymal acoustic path mainly consists of parenchymal tissue, relatively small blood vessels (arterioles, venules, capillary vessels) and a small amount of cerebrospinal fluid (CSF) (Fig. 2b). The ultrasound speed inside the parenchymal acoustic path mainly depends on the blood volume (CBV) inside this path. The ultrasound attenuation inside this path mainly depends on the parenchyma tissue volume [4,5],
- to measure the relative value of ultrasound speed changes inside the parenchymal acoustic path, this path is insonated by supershort ultrasonic pulses, and the time-of-flight measuring method is used,
- to compensate in a real-time and *in situ* the influences of the extracranial tissue hemodynamics on the results of such measurements, the same ultrasonic pulses and their echoes from internal surfaces of the skull are used [17],
- the specially designed software is used to convert the measured data into absolute or relative ICP or CPP values or into the cerebral blood flow autoregulation state estimating indices.

This is the only existing method of non-invasive monitoring of cerebral parenchyma microvessel hemodynamics.

Absolute ICP non-invasive measurement method. The concept of this method [3] is as follows:

- the eye artery is used as a natural "transducer" which has two segments - intracranial and extracranial. Intracranial segment is compressed by ICP. Extracranial segment can be compressed by the controlled external pressure applied to the tissues surrounding the eye ball,
- the pressure balance is achieved when the absolute value of external pressure P_{EXT} is equal to the ICP (Fig. 3a). In the case of balance the blood flow parameters in the intracranial segment and extracranial segment of the eye artery are almost equal independently of the absolute value of arterial blood pressure, hydrodynamic resistance of the eye veins, the pressure inside the eye ball and the initial absolute values of the blood flow parameters in both segments of the eye artery,

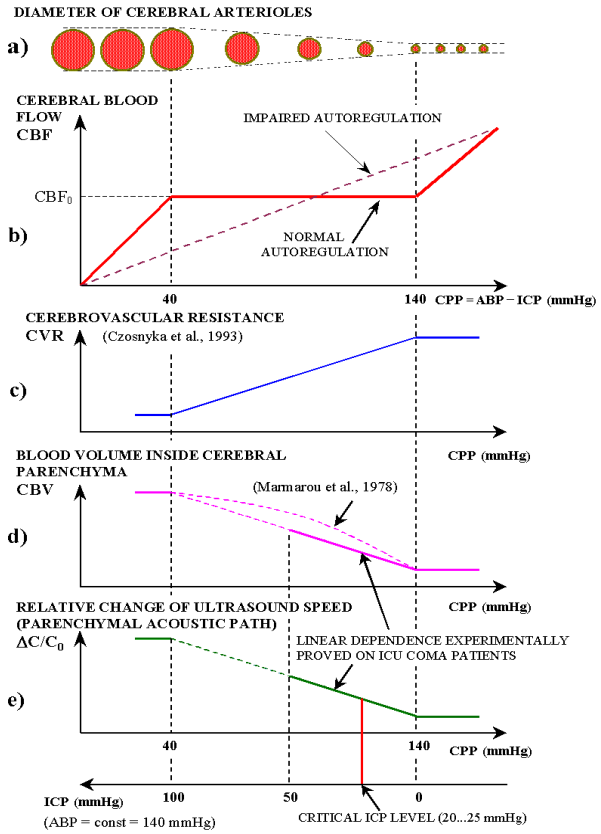

Fig. 1. Relationships between ultrasound speed in cerebral parenchymal acoustic path and CBF, CPP, ICP, ABP, CVR and CBV

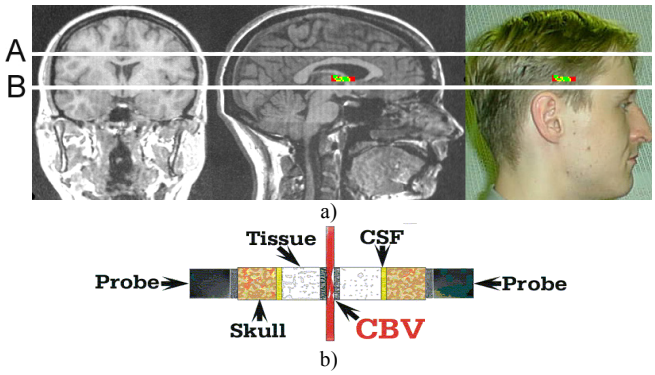

Fig. 2. The correct position of supraventricular (A - upper line) and intraventricular (B - lower line) transintracranial parenchymal acoustic paths (a) and structure of the microvascular acoustic path (c). The path consists of external tissues, skull bones and a transintracranial parenchymal acoustic path with the layers of blood, parenchyma tissue and CSF

- the specially designed two depth pulse wave transcranial Doppler device is applied to identify simultaneously the blood flow velocities in the intracranial segment V_I and extracranial segment V_E of the eye artery. The difference between those velocities ΔV is used to control the pressure in pneumatic camera which is in a sealing engagement with a perimeter around the eye. When pressure P_{EXT} in the pneumatic camera causes ΔV to approach close to zero value, in that case P_{EXT} becomes an indicator of the intracranial pressure absolute value, i. e. ICP = P_{EXT} (Fig. 3). The eye artery is used like a “scales” (Fig. 3a) in this method.

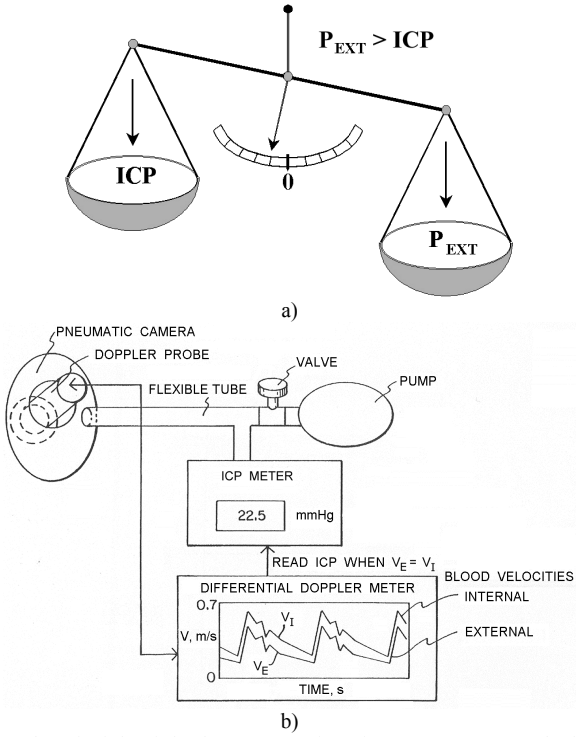

Fig. 3. The principle of absolute ICP non-invasive measurement method. The difference between V_I and V_E must by minimized up to zero for obtaining a balance between ICP and external pressure P_{EX} applied to the eye

This is the only existing concept of a non-invasive absolute ICP value measurement without the necessity to use individual calibration of the system "individual patient / non-invasive ICP meter". The preliminary clinical results of ongoing comparative invasive / non-invasive ICP study show that the resolution of this new method is up to ±3 mmHg.

III. Results

The new non-invasive ultrasonic Vittamed monitor based on the ultrasound speed in cerebral parenchymal acoustic path measurement and which includes a real-time and *in situ* compensation of the influence of the external tissue and skull bones to the measurement results was designed and tested in the intensive care units (ICU). The simultaneous ICP monitoring with a new non-invasive Vittamed monitor and Camino V420 invasive monitor was performed for ICU coma patients after a closed head injury. The clinical results of simultaneous ICP pulse waves, ICP reactions on the CO_2 reactivity and the long term ICP trend monitorings and are shown in Fig. 4 - Fig.6.

While attempting to prove a linear relationship between the non-invasively measured ultrasound speed in a cerebral parenchymal acoustic path and ICP, the readings from the invasive ICP monitor were plotted against the readings of a non-invasive ICP monitor (28 head injured patients) Fig 7a. The non-invasive ICP data were calculated from the time-of-flight measured data using the linear functions after the real-time and *in situ* compensation of the influence of the external tissue and skull bones on the measured time-of-flight data. This experimental result shown in Fig 7a is the evidence that the ultrasound velocity changes are linearly dependent on the ICP as it was explained in Fig.1 and predicted during the theoretical modeling of time-of-flight and blood volume relationship inside the transintracranial parenchymal acoustic path [4,5]. It is also very important that this linear relationship is wide enough (0 to 50 mmHg) and is above and below the critical ICP level.

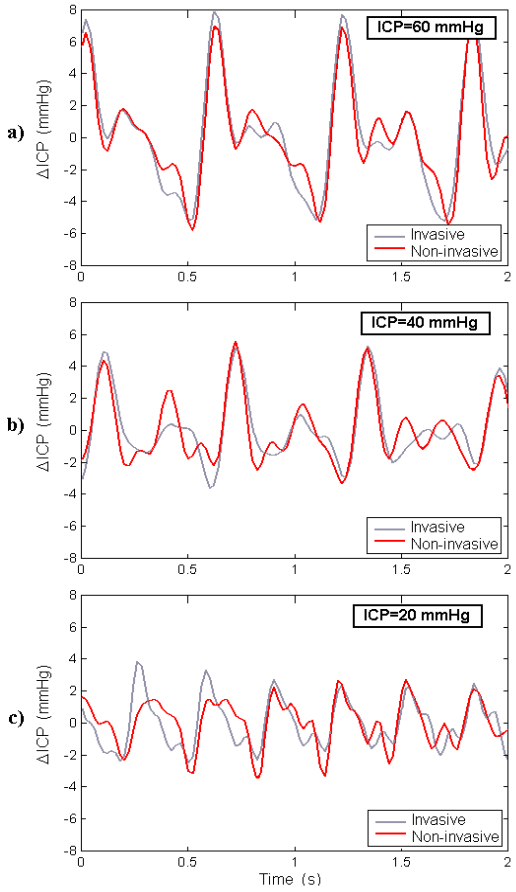

Fig. 4. Simultaneous invasive and non-invasive records of ICP pulse waves when ICP=60 mmHg (a), ICP=40 mmHg (b) and ICP=20 mmHg (c) applying invasive and non-invasive devices (head injured patient in coma)

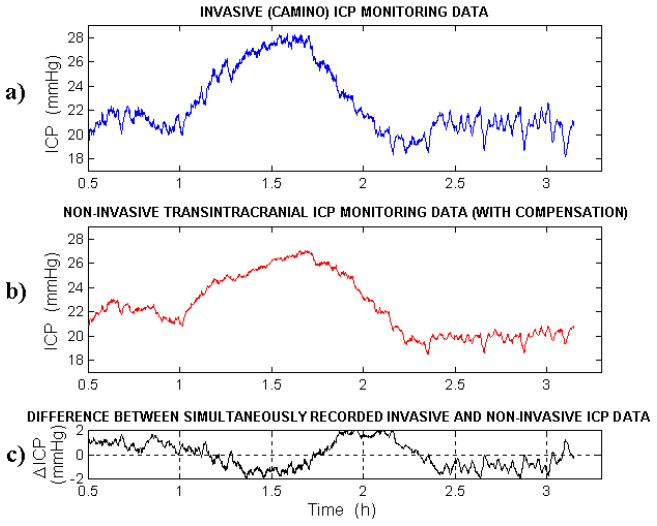

Fig. 5. Comparison of long term invasive and non-invasive ICP monitoring data in the intensive care unit (patient in coma after closed head injury)

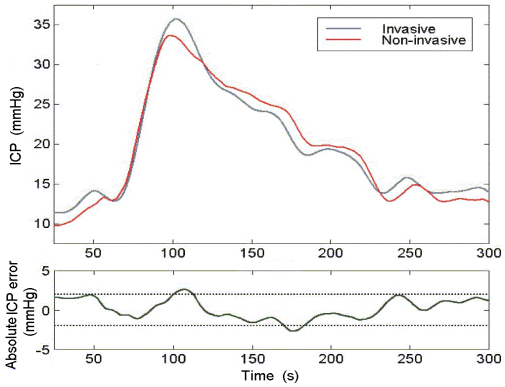

Fig. 6. Comparison of invasive and non-invasive ICP data during CO_2 reactivity tests

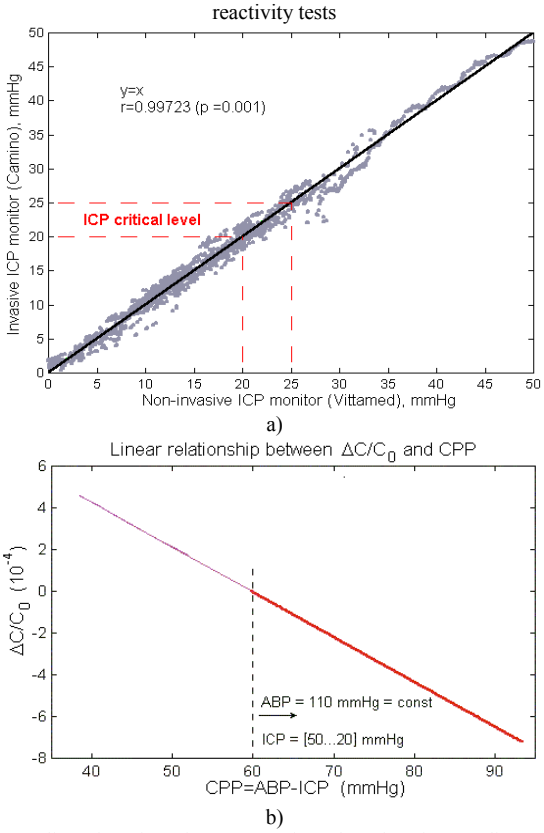

Fig 7. Readings from invasive ICP monitor plotted against readings of non-invasive ICP monitor (28 head injured patients) in (a). Relationship between the non-invasively measured ultrasound speed data and CPP in (b)

IV. Conclusion

1) The comparative studies of the new non-invasive ultrasonic Vittamed monitor based on the ultrasound speed in the cerebral parenchymal acoustic path measurement have been performed for the first time in ICU. The results obtained show that by applying the real-time and *in situ* automatic compensation of the influence of the extracranial tissue and skull bones on the measured data it is possible to achieve the uncertainty better than ±2 mmHg for the long term non-invasive ICP monitoring. The linear relationship between the ultrasound speed in the cerebral parenchymal acoustic path and the ICP has been proved by calculating the ICP data from the non-invasively measured time-of-flight data. Such relationship was obtained for the first time during the long term monitoring in a wide range of ICP values from 0 mmHg to 50 mmHg and it confirms the results obtained by mathematical simulation. The performed simultaneous invasive and non-invasive monitoring of the ICP pulse waves shows a good agreement between the measured data.

2) The innovative method is proposed for ICP absolute value non-invasive measurement, which is the only existing method which does not require individual calibration of the system "patient – non-invasive absolute ICP meter" [3].

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